TITLE

A LOGGING TOOL FOR MEASUREMENT OF RESISTIVITY THROUGH CASING USING METALLIC TRANSPARENCIES AND MAGNETIC LENSING

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/229,983, entitled “A Logging Tool For Measurement of Resistivity Through Casing Using Metallic Transparencies and Magnetic Lensing,” filed September 2, 2000; U.S. Patent Application No. 09/672,467, entitled “Magnetic Saturation and Coupling,” filed September 28,2000, which in turn claims benefit of U.S. Provisional Application No. 60/166,695, filed November 20 1999; U.S. Patent Application no. 09/672,755, entitled “Magnetic Lensing,” filed September 28, 2000, which in turn claims benefit of U.S. Provisional Application No. 60/166,693, filed November 20, 1999, U.S. Provisional Application 60/166,696, entitled “Spectral EM Frequency Metallic Thickness Measurement using Metallic Transparencies,” filed

November 20, 1999, and U.S. Provisional Application No. 60/222,982, entitled “Measurement of Electrical Properties Through Saturated Permeable Metals Using Directed Magnetic Beams and Magnetic Lenses” filed September 1, 2000.

BACKGROUND OF THE INVENTION

1. Field of Use

Any medium containing electrically conductive material can be monitored for changes in the electrical resistivity of the electrically conductive material within the medium. An important and well known

example is the measurement of the electrical resistivity of underground geologic formations. Such formations often contain salt water, which is a relatively high electrically conductive material and/or hydrocarbons which are less electrically conductive and therefore more electrically resistive. The resistivity of geologic formations containing these materials is measurable, thereby providing information relative to the concentrations of oil, water and gas at various locations within a geologic formation.

It has been demonstrated that it is possible to measure the resistivity of an underground geologic formation through a ferromagnetic Well Casing penetrating the formation, as well as through other materials that are electrically conductive and magnetically permeable. These materials are referred herein as "EM Barriers" or "Barrier Materials." The technology is based upon inductive magnetic coupling, therefore the measuring apparatus does not need to be in physical contact to the Barrier Material comprising the well casing or production tubing. The invention subject of this specification utilizes this technique to measure the resistivity of geologic formation beyond the well casing. The fact that the invention does not require physical contact with the surface of the casing or tubing material facilitates movement of the logging tool within the interior of the tubing or casing along the axis of the well. It also minimizes the wear upon the logging tool housing and other components.

Hydrocarbon production wells typically utilize an outer casing made of a ferromagnetic material. Common outside diameters of the casing may be of a range of 7 to 10 inches or larger. The interior diameter is of varying dimensions. The thickness of the casing also varies but may typically be ½ inch or more in thickness. Placed inside the permanent casing is a smaller production tubing. The outer diameter of the production tubing may be in a range of 1 to 4 inches. Hydrocarbon, such as crude oil mixed with salt water or solid particles such as sand, flows through the production

tubing at a high velocity. This environment is harsh and corrosive, sometimes requiring the replacement of the production tubing.

Note that throughout this specification, the terms "Casing" and "Well Casing" will be deemed to include hydrocarbon production tubing or other ancillary structures such as casing or tubing connectors or couplings that may be installed inside of the well casing.

The Logging Tool of this invention creates a Metallic Transparency"™ local to its oscillating magnetic flux transmitter (Transmitter) and its flux signal receiver (Receiver) by means of a strong magnetic flux field saturating the proximate portion of the Barrier Material comprising the Well Casing near the Transmitter and Receiver. It may also utilize partial saturation and Magnetic Lensing to direct the oscillating flux of the Transmitter in a controlled manner.

The present invention relates generally to measuring resistivity of media such as liquids, gases or other objects within a geologic formation surrounding a Well Casing. Specifically, the present invention relates to through casing resistivity measurement in downhole hydrocarbon production environments. The present invention provides an logging apparatus and method for measuring the resistivity of a formation proximate to a well. The current invention, in one embodiment, is an apparatus that can be moved inside the Casing of an oil or gas producing well for measuring the resistivity of the surrounding formation. The apparatus records magnetic signals that relate to the resistivity of the geologic formation at various depths or locations within the formation penetrated by the Cased well as the logging apparatus moves along the axis of the well. The apparatus can thereby detect the location and amplitude of said resistivity in single or multiple directions, and at distances that will help operators of wells adjust their production management and their reservoir management activities. The apparatus can also be used to

detect changes in the resistivity of over time by comparison of recorded signals.

The invention includes a Logging Tool that can travel through the relatively narrow diameter of Well Casing (or production tubing), means to raise and lower the Tool, means to supply power and receive data, as well as recording and display devices.

2. <u>Description of Related Art</u>

In the development and production of oil and gas reservoirs, there is a very significant need to increase the amount and accuracy of information regarding the composition and changes in the composition of the resource-bearing zones of the formation. Resistivity measurement has long been used to characterize properties of the immediately surrounding substrates prior to the inception of production. However, it has typically only been possible to take such measurements prior to setting Casing or while the formation itself is otherwise "exposed" to the logging tool, i.e., an "open hole" without an interceding material that acts as a barrier between the logging tool and the formation substrate. Existing methods of measuring the resistivity of the media within a geologic formation have therefore required that the measurements be taken with logging tools deployed prior to commencement of actual production. After casing is placed in the well and production is underway, it is generally not possible to measure the resistivity of the surrounding geologic formation without interruption of the well production and penetration or removal of the Well Casing.

As is known to those skilled in the industry, the electrical resistivity of a geologic formation varies as a result of (among other reasons) the changing proportion of hydrocarbon to water contained within the formation. Having the ability to measure at selected locations and directions over time would provide for the unique ability to monitor, for

example, the change in the percentage of water versus either oil, gas, or other electrically conductive materials approaching the well, far in advance of such change in fluids actually entering the well. The benefits of such measurements include the ability to see changes in the composition of the formation, i.e., hydrocarbon and water by measuring changes in the resistivity of the formation through the Barrier Material comprising the Well Casing.

Numerous attempts have been made to provide an apparatus or method for measuring the electrical resistivity of the surrounding geologic formation through a Well Casing. See for example U.S. Patent No. 5,654,639 entitled "Induction Measuring Devices in the Presence of Metal Wall," but requiring an electric current to be passed into the metal pipe wall. The contact device is then disengaged from the wall when the apparatus is moved. Also U.S. Patent No. 5,426,367, entitled "Logging of Cased Well by Induction Logging to Plot an Induction Log of the Well" and stating the device "needs the most intimate contact with the pipe in order to eliminate 'air gaps' and still maintain mechanical integrity." Column 8, Lines 40 – 43. U.S. Patent No. 6,157,195, entitled "Formation Resistivity Measurements from within a Cased Well Used to Quantitatively Determine the amount of Oil and Gas Present," also requires the transmission of an AC current through the Well Casing to a remote electrode. This is consistent with earlier patents such as U.S. Patent No. 6,025,721, entitled "Determining Resistivity of a Formation Adjacent to a Borehole Having Casing by Generating Constant Current Flow in Portion of Casing and Using at Least Two Voltage Measurement Electrodes," U.S. Patent No. 5,260,661, entitled "Calibrating and Compensating Influence of Casing Thickness Variations on Measurements of Low Frequency AC Magnetic Fields within Cased Boreholes to Determine Properties of Geological Formations," U.S. Patent No. 5,065,100, entitled "Measurement of In-

phase and Out-of Phase Components of Low Frequency AC Magnetic Fields within Cased Boreholes to Measure Geophysical Properties of Geological Formations," and U.S. Patent No. 5,038,107, entitled " Method and Apparatus for Making Induction Measurements Through Casing."

Many of these methods have relied upon the transmission of an electrical current through the Casing and into the surrounding formation. All of the methods have required electrical contact be maintained between the apparatus and the Casing.

Thus, there has always been a need to provide the capability for continuous or periodic measurements of formation resistivity for a permanent hydrocarbon production well installation. Specifically, there has been a need to "see through" the Well Casing to the geologic formation located the production well. There also has long been a need to provide resistivity measurements without interruption of the hydrocarbon production well. There is also a great need for the ability to simultaneously (i) generate a magnetic flux, by conventional means, within the confines of a hydrocarbon production well, (ii) create magnetic transparency zone within or through the Well Casing of a hydrocarbon production well, (iii) engage or transmit through the Transparency with oscillating magnetic flux, and (iv) receive and measure through the Well Casing magnetic flux that may be generated in the media in the geologic formation outside of the Well Casing. It is already known to those skilled in the art that such measurements can provide information about the resistivity of media within the formation, and hence the composition or change in the media within the geologic formation proximate to the well.

SUMMARY OF THE INVENTION

The invention subject of this specification provides a method and apparatus for measuring the electrical resistivity of the geologic formation

proximate to a hydrocarbon production well installation. A measuring device ("Logging Tool") is configured to allow it to be moved through the axial length of the Well Casing. Well Casing (including hydrocarbon production tubing) is commonly manufactured of materials that are electrically conductive and magnetically permeable. These materials are referred herein as "EM Barriers" or "Barrier Materials." The present invention creates at least one Metallic Transparency within or through the Well Casing. A Metallic Transparency permits oscillating magnetic flux to be transmitted through the Casing.

The Logging Tool of the invention further includes the capability of generating magnetic flux to magnetically engage and saturate a portion of the Well Casing (utilizing a "Magnetic Transparency Generator" or "Saturation Inducer"), transmitting oscillating magnetic flux into or through the Transparency and measuring any oscillating magnetic flux generated by the eddy currents induced within electrically conductive material existing within the geologic formation, e.g., water or hydrocarbons. It will be readily understood that the transmission of oscillating magnetic flux into an electrically conductive material will induce an electric current, i.e., eddy current, by well know scientific principles. The present invention also provides the ability to perform these activities continuously as the Logging Tool is moved through the axial length of the Well Casing.

By altering the concentration of the Saturation Flux, the frequency of the Transmitter flux, placement of the Transmitters and Receivers, or by the orientation of the Transmitter in relation to the Saturation Coil, it is possible to vary the depth of penetration into the geologic formation, thus building a detailed characterization profile of the formation at various distances from the casing. The Metallic Transparency may also be used to directionally control the flux transmitted through the casing and into the surrounding geologic formation. This may be accomplished by Magnetic

Lensing™

In practicing the invention, it is useful to know the electrical conductivity and permeability of the Well Casing. This allows the optimization of the input frequency, amplitude and power. It will be appreciated that these properties of the Well Casing can be expected to vary as the apparatus of the invention moves along the interior of the casing or production tubing. To eliminate the effects of a varying permeability in a Well Casing, it is preferable to continuously monitor the electrical conductivity and permeability casing or tubing. It is intended that in creating the desired Metallic Transparency, the effect of the Well Casing upon the transmitted and received signals is minimized by the permeability of the Well Casing being reduced to as close to unity as possible while the frequency of the magnetic flux from the Transmitter is varied. When the permeability of the Well Casing is close to unity, total or near total saturation of the Well Casing is achieved. Then, with the frequency magnetic flux held constant, change in the amount of the transparency varies the permeability. This is accomplished by varying the saturation value. The Conductivity of the Well Casing is measured by creating a Metallic Transparency, subjecting this transparent area to varying frequencies and monitoring the received signal. The last transmitted signal detected at the Receiver determines the conductivity of the Well Casing when at total saturation.

There are a plurality of subsystems that may be incorporated into the invention. These include the following:

Full Saturation Magnetic Flux Circuit

Partial Saturation Magnetic Flux Circuit

Transmitter/Receiver System

Nulling System – geometric, electronic, permeability

Automatic Lensing System

Conductivity/Resistivity Measurement System

Wall Thickness Measurement System

Each of these subsystems is incorporated into the preferred embodiment of the Logging Tool. Each will be discussed as part of the subject invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate preferred embodiments of the invention. These drawing, together with the general description of the invention given above and the detailed description of the preferred embodiments given below, serve to explain the principles of the invention for resistivity measurement of geologic formations from within an installed ferromagnetic casing or similar material.

Figure 1 illustrates a schematic outline of some of the components utilized in the invention for creating Metallic Transparencies"□ and transmitting and receiving magnetic flux.

Figure 1A illustrates an alternate schematic outline of some of the components utilized in the invention.

Figure 2 illustrates an embodiment of the invention whereby an oscillating magnetic flux saturates a Well Casing and a second, higher frequency oscillating flux is transmitted through the Well Casing during the time of saturation.

Figure 3 illustrates an embodiment of the invention contained within a housing and having the Transmitter and Receiver in a bistatic configuration.

Figure 3A illustrates the multiple depths of penetration achieved in

the near field utilizing multiple Receivers.

Figures 4A illustrates an embodiment of the Magnetic Transparency Generator component of the invention utilized to engage or couple to the Well Casing with Magnetic Flux.

Figure 4B illustrates an alternate embodiment incorporating a Magnetic Culminator as part of the Magnetic Transparency Generator.

Figures 4C and 4D illustrate alternate embodiments of the invention utilized to couple or saturate the Well Casing incorporating Magnetic Culminators.

Figures 5A and 5B illustrate additional alternate embodiments of the invention utilized to couple or saturate the Well Casing.

Figures 5C and 5D illustrate a single Magnetic Transparency Generator incorporating both a Transmitter and Receiver configured to conform to the interior dimension of the Casing.

Figure 5E illustrates a Magnetic Culminator incorporating a Transmitter and Receiver and configured to conform to the interior dimension of the Casing.

Figure 6A illustrates magnetic coupling between two unlike magnetic poles through a Well Casing

Figure 6B illustrates the magnetic flux lines within the Well Casing proximate to two like magnetic poles.

Figure 6C illustrates the magnetic flux lines penetrating the Well Casing proximate to a Magnetic Culminator.

Figure 7 illustrates an embodiment of the invention comprising a monostatic configuration with the Receiver nested proximate to the Transmitter.

Figure 8 illustrates another embodiment of the invention comprising a multiple array of Transmitters and Receivers.

Figure 9 illustrates an embodiment of the invention for placement of

a Receiver and Transmitter upon a Magnetic Culminator or Saturation Core of the invention.

Figure 10 illustrates yet another embodiment of the invention.

Figures 10A and 10B illustrate a cross sectional views depicting alternate embodiments of the Saturation Coil shown in Figure 10.

Figures 11, 12, 13A, 13B, 14A and 14B illustrate embodiments of Magnetic Lensing.

Figures 15 through 19 illustrate further embodiments of Magnetic Lensing utilized in the invention.

Figure 20 illustrates the relationship between the frequency of oscillating magnetic flux and depth of penetration into the Well Casing.

Figures 21A, 21B, and 21C illustrate the relationship between the Transmitter Current amplitude (Figure 21A), the Saturation Current amplitude (Figure 21B), and the Receiver Signal amplitude (Figure 21C). Figure 22 illustrates one embodiment of a bistatic Magnetic Transparency Generator of the present invention

Figure 23 illustrates the relationship between the flux density (and the change in magnetic field intensity H (ΔH) in amp-turns/meter.

Figure 24 illustrates the relationship between the Receiver amplitude A_{Rx} and H in amp-turns/meter.

Figure 25 is a graph of amplitude versus time for a bistatic configured Magnetic Transparency Generator of the present invention coupling with differing Barrier Materials.

Figure 26 illustrates an embodiment of the method of practicing the invention showing the sequential steps of the method.

Figure 27 illustrates an experimental apparatus utilized to demonstrate the invention's ability to measure changes in resistivity in media outside a well casing.

Figure 28 illustrates the experimentally measured changes in

resistivity of the media outside the casing, as measured from within the Well Casing.

Figures 29, 30 and 31 illustrate other embodiments of the present invention.

Figure 32 illustrates use of the oscillating Transmitter Signal damping the Saturation Current.

The above general description and the following detailed description are merely illustrative of the subject invention, and additional modes, advantages, and particulars of this invention will be readily suggested to those skilled in the art without departing from the spirit and scope of the invention.

DETAILED DESCRIPTION OF THE INVENTION:

The invention subject of this specification provides a method and apparatus for measuring the electrical resistivity of the geologic formation proximate to a cased well such as a cased hydrocarbon production well. Well Casing (the term used herein to include hydrocarbon production tubing or other ancillary structures such as casing or tubing connectors or couplings) commonly is manufactured of materials that are electrically conductive and magnetically permeable, i.e., "EM Barriers" or "Barrier Materials." Such materials include ferromagnetic and paramagnetic materials.

The present invention includes the creation of transparencies or windows ("Metallic Transparencies"™) within such Barrier Materials comprising the Well Casing, thereby allowing the passage of oscillating magnetic flux into or through the Well Casing. In simple terms, the invention works in the following steps: (1) a Saturation component (Saturation Inducer or Magnetic Transparency Generator) containing a "Saturation Coil", preferably wrapped around a highly permeable core

("Saturation Core"). When the Saturation Coil is energized, it acts as an electromagnet. The Saturation Coil creates one or more fields of magnetic flux ("Saturation Current" or "Saturation Flux") adjacent or near the Well Casing. The Saturation Flux engages with the adjacent Well Casing and creates a partial or full magnetic saturation of the Well Casing proximate to the Saturation Coil. Saturation results in the magnetic permeability of the Well Casing being substantially lowered. When fully saturated, that portion of the Well Casing cannot absorb further magnetic flux, thereby allowing additional flux to pass through the Well Casing. When partially saturated, the Well Casing acquires greater capacity to engage or couple with magnetic flux, especially magnetic flux oscillating at relatively high frequencies. In such a state, that portion of the Well Casing has become "transparent" to magnetic flux. This partially or fully saturated section is known as a "Transparency" or a "Metallic Transparency". (2) One or more magnetic flux transmitter components ("Transmitters"), each utilizing one or more coils ("Transmitter Coil") located proximate to a Metallic Transparency, then create one or more fields of additional magnetic flux oscillating at frequencies preferably equal to or greater than the Saturation Flux. This oscillating magnetic flux ("Transmitter Signal," "Sensing Signal" or "Transmitter Flux") is engaged with the section of full or partial saturation (having greatly reduced magnetic permeability) allowing the Transmitter Flux (or other oscillating magnetic flux induced by eddy currents within the partially saturated Casing) to pass through the Metallic Transparency of the Well Casing and enter the surrounding geological formation. (3) Electrically conductive media, e.g., water or hydrocarbon, contained within the surrounding formation interact with this oscillating magnetic flux. Through basic electromotive forces, a separate oscillating magnetic flux is induced in the electrically conductive media contained within the formation. (4) The field of this induced magnetic flux extends

back to the Well Casing. As in step No. 1 above, the same or similar Saturation Coils create a Transparency near a separate coil ("Receiver Coil") so that the induced magnetic flux of the geologic formation can be received and measured by this Receiver Coil located inside the Casing. (5) The Receiver component, of which the Receiver Coil is part, converts the induced flux ("Receiver Signal") into electrical signals ("Receiver Current") that are filtered and processed in order to determine the electrical resistivity of media located in the geologic formation proximate to the Well Casing. The Receiver Signal is electrically processed to concentrate and magnify the induced oscillating magnetic flux, thereby forming the Receiver Signal. The Transmitter Flux (or Transmitter Signal) is nulled to minimize direct transmission of flux from the Transmitter to the Receiver. The Transmitter Signal is compared to the Received Signal and, using the changes in amplitude and phase, the electrical resistivity of the media in the surrounding geologic formation is determined and displayed. These signals may then be sent to the Output display for further processing, display, and recording. The Output display, power supply, and other ancillary equipment may be located at the well head or surface.

Accordingly, the method and apparatus of the invention includes the capability of generating magnetic flux ("Saturation Flux" or "Saturation Current") to engage and magnetically saturate a portion of the Well Casing, thereby creating a Magnetic Transparency. The invention also includes the capability to generate and transmit one or more oscillating magnetic flux ("Transmitter Signal" or "Transmitter Flux") into or through the Metallic Transparency created in the Well Casing. The invention also includes the capability to receive and measure any magnetic flux ("Receiver Signal") induced in the geologic formation proximate to the Well Casing and penetrating through a Metallic Transparency in the Well Casing.

As will be discussed in greater detail below, the preferred embodiment of the invention will include the ability to generate and send a plurality of Transmitter Flux of differing frequencies, either simultaneously or sequentially. The preferred embodiment will also include the ability to detect and measure Receiver Signal from a plurality of directions. A preferred embodiment will also have the capability to partially saturate one or more portions of the Well Casing in order that one or more frequencies of oscillating magnetic flux may be induced in and focused or directed through partially saturated Well Casing utilizing Magnetic Lensing™.

The preferred embodiment of the invention will also incorporate one or more means to null direct coupling of magnetic flux signal between the Transmitter and Receiver, i.e., the direct transmission of the Transmitter Current to the Receiver Coil. In addition, a preferred embodiment of the invention will include means to accurately measure changes in Casing properties, e.g., conductivity, permeability and thickness.

It will be appreciated that there is a plurality of components or subsystems in the invention.

These include the following:

Full Saturation Magnetic Flux Circuit

Partial Saturation Magnetic Flux Circuit

Transmitter/Receiver System

Nulling System – geometric, electronic, permeability

Automatic Lensing System

Conductivity/Resistivity Measurement System

Wall Thickness Measurement System

All or some of these subsystems may be incorporated into the preferred embodiment of the Logging Tool subject of this invention. Each will be discussed in greater detail below.

1. Full Saturation Magnetic Flux Circuit

The design of the Saturating Magnetic Flux system (hereinafter "Saturation Circuit," "Saturation Inducer" or "Magnetic Transparency Generator") allows the reduction of the permeability of the adjacent portion of Casing to near 1 henry/meter. It will be appreciated by those skilled in the technology that the Barrier Material comprising the Well Casing, e.g., carbon steel, may have relative permeabilities in excess of 10,000 at a typical magnetic flux density. A fully saturated portion of the Casing is, however, transparent to the transmission of additional magnetic flux. In this state of full saturation, the fully saturated or transparent portion of the Casing can not absorb further magnetic flux. Therefore, a second and oscillating magnetic flux from the Transmitter of the invention will penetrate through the Transparency of the Casing and into the surrounding geologic formation. It is therefore possible to measure the electrical resistivity of the geological formation proximate to the Transparency created in the Casing. The depth of penetration of the oscillating magnetic flux into the media within the near field of the saturated Casing is proportional to the separation distance between the Transmitter and Receiver of the invention. This is very useful for near Casing measurements. A series of Receivers placed at varying distances from a single Transmitter could establish various depths of measurement directionally into the surrounding geological formation proportional to these separations. It will be noted, however, the as the separation distance "D" between the Transmitter and Receiver(s) is increased, the density of the flux decreases at a rate of $1/D^3$ and that when the Well Casing is fully saturated, i.e., its relative permeability approaching "unity" or 1, Magnetic Lensing can not be utilized.

2. Partial Saturation Magnetic Flux Circuit

When in a state of partial saturation, the effected portion of the Well

Casing can be used for Magnetic Lensing. Simply stated, when partially saturated, the permeability of the Casing is substantially reduced, thereby allowing greater penetration by the oscillating Transmitter Signal, particularly at higher frequencies. However, the relative permeability of the Casing is greater than 1 henry/meter. The partially saturated Casing continues to absorb a significant portion of the Transmitter Signal. Since the Casing is also electrically conductive, eddy currents are generated within the Casing. Oscillating magnetic flux induced by the eddy currents is emitted from the Casing into the geologic formation. The reduced permeability can be utilized to control and concentrate this induced magnetic flux emitted from the partially saturated Casing. The partially saturated Casing therefore acts as a lens to concentrate and direct oscillating magnetic flux transmitted into the surrounding geologic formation. This allows measurement of the electrical resistivity of media within the formation and more distant from the Well Casing than can be achieved by controlling the separation distance between the Transmitter and Receiver.

If a Partially Transparent volume region is created, a separate oscillating EM wave is transmitted into this Partially Transparent volume region, preferably of a higher frequency than the first EM energy source. Eddy currents are generated in the Partially Transparent Material. An oscillating magnetic flux is induced by these eddy currents. At least some portion of the magnetic flux from this induced magnetic field is transmitted out from the Partial Barrier Material. However, the lines of flux are bent or altered as they are emitted out from the surface of the Partially Saturated Material into the surrounding environment. This bending of magnetic flux can be controlled, allowing the lines of magnetic flux to be focused on an Object existing on the opposite side of the Barrier Material from the MTG transmitter. This focusing partially counteracts the normal rapid geometric

spreading of magnetic flux. Concentrating the magnetic flux allows distant sensing using much less power. When utilized in this manner, the MTG includes a Magnetic Lens™ capability.

3. Transmitter/Receiver System

There may be a multiplicity of Transmitter/Receiver configurations and orientations.

(a) Transmitter – There may be more than one Transmitter arranged directionally around the Casing. In addition, multiple Transmitter Signals of the same frequency may be bucked with respect to each other to propagate the Transmitter Flux further out into the geologic formation. Also this bucking or interaction among magnetic flux oscillating at the same frequency may be used to direct Transmitter Flux in a controlled manner. A plurality of Transmitters may be configured to achieve a desired Transmitter Signal geometry.

(b) Receiver – There may be a plurality of Receivers used in an evenly or unevenly spaced array. Receiver's may be bucked or used to enhance the signal or establish directionality of received signals.

4. Nulling System

The Receiver system must be nulled with respect to the Transmitter system. This nulling prevents the Receiver system from being overwhelmed by the signals emitted from the Transmitter system. It also minimizes the interference of extraneous electrical signals, i.e., electrical noise. It has been found that a combination of three nulling techniques provides the best results. These three systems are (a) Geometric, (b) Electronic, and (c) Transmitter Signal Absorption by Permeability.

(a) Geometric nulling – A wide combination of geometric nulling systems may be used. The respective design and location of each Transmitter and Receiver may vary in consideration of the placement and

design of the other Transmitters or Receivers and in consideration of the location and geometry of the Magnetic Transparency. Therefore, by not wrapping either the Transmitter or Receiver Coils, or both, around the Saturation Inducer of the Casing allows a number of advantages. These are:

1. Mechanical nulling by Receiver or Transmitter placement or rotation with respect to each other, or with respect to the Casing.

2. Directionality by being nearest the Casing side of the Saturation Core, or by rotation of the axis of the Transmitter or the Receiver.

3. Minimizing possible saturation of the Saturation Inducer core that would cause uncontrolled dispersion of Saturation Flux. The dispersed Saturation Flux may achieve only partial saturation of a selected portion of the Well Casing. This may be a desired result. This is exactly opposite the concern cited in U.S. Patent No. 5,038,107 which does not want to use an AC current on the Saturation Inducer Core that may take the walls or core out of saturation.

4. Since the Transmitter Coil can have an air core, laminated core or smaller inductor core than the Saturation Inducer core, much higher frequencies can be used for the Transmitter Signal. This due to the inductive impedance resulting from the presence of a large metallic Saturation Core. This large Saturation Core drives up the total impedance.

5. Multiple Transmitters, each at different frequencies, may broadcast simultaneously to perform spectroscopy over a large frequency range.

6. Transmitters comprised of differing coil geometry will have different Flux Signal geometry. Therefore varying the design of the Transmitter, e.g., varying the coil length, may also be used to control the portion of the surrounding formation that will be investigated.

7. For applications utilizing full saturation of a portion of the Well

Casing, the Transmitters and Receivers must be placed in sufficient proximity to the Metallic Transparency to prevent a large amount of either Transmitter Signal or Receiver Signal being absorbed into the non-saturated high permeability Casing.

8. Multiple Transmitters can be used to "buck" each other, thereby causing the geometry of the Transmitter Flux to be altered. This may achieve a greater penetration into the surrounding formation without utilization of Magnetic Lensing.

9. Multiple Receivers can be either nulled with respect to each other and/or built into an array for improving signal receiving resolution. These techniques may incorporate reversing the direction of at least one of the Transmitter Coils or altering the length of at least one of the Transmitter Coils in relation to the other(s).

(b) Electronic nulling – In this nulling type, it is possible to either null by creating a Receiver Signal 180° out of phase and exactly in reverse amplitude to the Transmitter Signal. Another method is measuring the Receiver Signal attributable to direct coupling of the Transmitter Signal and subtracting this value from all other measured values of Receiver Signals.

(c) Permeability nulling – In this nulling method, a variety of ways may be used to absorb the Transmitter Signal before it reaches the Receiver. This may be accomplished by separating the Transmitter and Receiver by enough high permeability material to absorb the Transmitter Signal before it reaches the Receiver Coil. Another absorption method is to isolate the Transmitter from the Receiver by highly permeable materials such as EM Barriers or by placing the Receiver Coil a large enough distance from the Transmitter such that the Transmitter Signal is absorbed prior to reaching the Receiver Coil.

5. Automatic Lensing System

One variation of the invention utilizes an oscillating Transmitting

Current penetrating a Partially Transparent Material. This oscillating current induces eddy currents within the Casing. The eddy currents induced within the Partially Transparent Casing induce a separate oscillating magnetic flux. The field of this oscillating magnetic flux radiates out of the Partially Transparent Casing and into the surrounding geologic formation. This oscillating magnetic flux will generate separate eddy currents within the effected region of the electrically conductive media of the geologic formation.

In this manner, the Casing serves as an antenna for the transmission of oscillating magnetic flux. In addition, the Magnetic Antenna™ capability of the Casing can be utilized to focus or direct the second and separate oscillating magnetic flux in a controlled manner. This feature is termed “Lensing” and the component termed a Magnetic Lens™.

There is a relationship between the amount of power utilized by the Saturation Inducer required to achieve partial saturation and the power utilized by the Transmitter. This relationship can be used to optimize the Magnetic Lensing effect and the strength of the Receiver Signal. When the Transmitter and Receiver are separated in a bistatic configuration, it has been found that optimized signal strength is achieved by increasing the Saturation Current proximate to the Receiver by as much as a factor of four over the power utilized to create the Partial Transparency proximate to the Transmitter. This enhances the Transparency of the Casing proximate to the Receiver. This relationship between the magnetic flux for the Receiver and Transmitter can be derived by known methods. This relationship varies as the casing metal thickness varies and as the permeability and conductivity also vary.

6. Conductivity, Permeability Measurement System

To perform accurate measurements of the media outside the Casing, the properties of electrical conductivity and magnetic permeability.

(a) The conductivity is measured at every new reading in the Casing by analyzing the frequency spectral response over a sufficient range to measure the effects of conductivity on the various frequencies.

(b) The permeability of the casing exhibits a functional relationship to the strength of the saturating coils. Therefore, at each location the power of saturation flux is varied. The frequency of the flux is maintained constant. The change in casing permeability responsive to changes in the saturation flux density is monitored.

7. Wall Thickness Measurement System

Once the conductivity and permeability are determined, an algorithm to calculate the wall thickness has been developed. This algorithm is straightforward and is useful to detecting the variations of wall thickness to corrosive or ablative conditions.

Reference will now be made in detail to the present preferred embodiments of the invention as described in the accompanying drawings.

Figure 1 illustrates schematically one embodiment of the components of the Logging Tool **500** subject of the invention. The components of the Logging Tool that are utilized within the Well Casing are contained within the Logging Tool Housing **572**. This Logging Tool includes (a) a Saturation Inducer **501** for creating a Metallic Transparency through the Well Casing and comprising a Saturation Coil **551**,(b) a Magnetic Flux Transmitter component **300**, comprising the Transmitter Coil **301**, a switch **562**, and a low noise amplifier (LNA) **564**, (c) a Receiver component **580** for the receipt and measurement of magnetic flux penetrating through the Well Casing and comprising a Receiver Coil **581**, (d) a frequency generator **563**, (e) a pulser **566**, (f) one or more capacitors **561** and (g) a nulling device **582**. The Saturation Inducer, includes the Saturation Coil **551**, Saturation Core or Magnetic Culminator (not shown). The Saturation Inducer **501**, Saturation Coil **551**, the Transmitter **300**,

Transmitter Coil **301** and any associated core (not shown), the Receiver **580,** including the Receiver Coil **581**; and the associated components described above and depicted within the Logging Tool Housing **572**, can be lowered into, maneuvered through and raised out of a Well Casing. The Output Display **583**, operator controls (not shown) and power source **560** are typically located at the well head or surface and linked to the Logging Tool Housing **572** by means of standard cables and connectors **568** and **588**. The operator's console or display **583** may also record and display historical trends of resistivity.

Figure 1A illustrates an alternate embodiment utilizing a high voltage and low voltage power source. The low voltage power source may be utilized for the Transmitter Signal and for the Digital Signal Processor. The high voltage power source may be used with an amplifier for desired amplification of the Transmitter Signal. A DC power supply is preferably used for generating the Transparency Current (Saturation Flux). It may also be found to be advantageous to utilize an analog to digital signal converter. It is envisioned that such a converter, as well as other sub-components, may be contained within the Electronic Component **570** discussed above.

The Saturation Coil **551** is a principle element of the Saturation Inducer **501**. It may be utilized in conjunction with one or more Transmitter components, Receiver components, or combinations of both. The Saturation Coil generates a magnetic flux that engages (or couples) with and saturates a portion of the Well Casing. The Transmitter Coil **301** is the principle element of the Transmitter component ("Transmitter") **300**. The Transmitter creates the oscillating magnetic flux that engages with and is transmitted through a magnetically saturated portion of the Well Casing (not shown).

When the Well Casing is saturated with magnetic flux from the

Saturation Inducer, one or more additional magnetic flux from the Transmitter **300** may pass through the Well Casing into the surrounding geologic formation. Preferably, the Saturation Coil generates a low frequency or constant magnetic flux. The oscillating magnetic flux of the Transmitter will preferably be at a higher frequency than the frequency of the Saturation Flux. In the preferred embodiment of the invention, the Transmitter has the capability to generate a plurality of separate magnetic flux, each having distinct frequencies.

The Receiver **580** may be combined with a separate Saturation Coil, thereby allowing the Receiver to be placed away from the Transmitter. This has a number of advantages, including facilitating nulling between the Transmitter and Receiver. An embodiment of the Logging Tool of the present invention in which the Transmitter and Receiver are located proximate to separate Saturation Inducers is termed a "bistatic arrangement" or "bistatic configuration."

The Saturation Coil **551** and Saturation Core **552**, the Transmitter Coil **301** and the Receiver Coil **580**, are often depicted separately from the other components described above and depicted within the "Electronics Component" **570**. For clarity, many of the drawings contained within this specification do not depict the Electronics Component. Further, the drawings may show an illustration of a coil only, but may be variously labeled as a Saturation Inducer, Transmitter or Receiver. It is understood that the other components or sub-components are deemed to be included as necessary. In addition, the components of the invention, including but not limited to the Saturation Coil, Transmitter Coil and Receiver Coil are not placed in physical contact with the Casing.

Figure 2 illustrates a graph of current versus time with respect to the present invention. Figure 2 illustrates three significant features in practicing the present invention: the level or quantity of Saturation Current

(or Saturation Flux) required to achieve saturation through the Casing **420**, the higher frequency or Transmitting Signal (or Sensing Signal) **411** and, as compared with the Transmitter Signal, the lower frequency of the actual Saturation Flux **401**. The higher frequency Transmitter Signal **411** is imposed on the lower frequency Saturation Flux **401**. Figure 2 illustrates the higher frequency oscillating Transmitter Signal as spikes **411** disposed along a lower frequency oscillating Saturation Flux **401**. In one embodiment of the present invention, the Transmitter Signal **411** may be transmitted only during the duration of each cycle of the oscillating Saturation Flux **401** that is above the level **420** required for saturation. Among other advantages, the latter embodiment minimizes energy consumption. In the latter embodiment, it is possible to have multiple transmissions of Transmitter Signal **411** during each phase that the Saturation Flux **401** is above the saturation level **420**.

The Saturation Flux **401** may not achieve the level of current (flux density) necessary to saturate the targeted area of the EM barrier material comprising the Casing. However, when partially saturated, the Casing will allow a significantly greater portion of the distinctively higher frequency Transmitter Signals **411** to couple, i.e., penetrate, into the Well Casing to generate eddy currents within an area of partial saturation or, alternatively, be of sufficient magnitude to saturate a portion of the Well Casing when combined with the Saturation Flux and therefore allowing the Transmitter Signal to directly penetrate through the Casing. In another embodiment, the Transparency Current may be generated from at least one permanent magnet, a low frequency AC current or a direct current DC electromagnetic device.

Illustrated schematically as an apparatus in Figure 1 and conceptually in Figure 2, the Saturation Coil **551** generates the Transparency Current (Saturation Flux) which in turn creates the Metallic

Transparency in the Casing. The Saturation Coil is comprised of conductive material preferably wrapped around a highly permeable core (Saturation Core or Flux Circuit Core) and powered either by DC current or a current oscillating at a low frequency. The Transmitter Signal **411** may be generated by the Transmitter **300**, comprised of the coil **301** of conductive material, powered by alternating current, preferably at a controlled frequency, wrapped upon or near the Saturation Coil **551**. Preferably, the Transmitter Signal is at a higher frequency than the Transparency Current. It is preferred that the frequency of the Transmitter Signal be at least a multiple of 10 greater than the frequency of the Transparency Current (also termed Saturation Flux). As discussed above, the higher frequency of the Transmitter Signal relative to the Transparency Current allows, for example, 10 wavelengths of the Transmitter Signal to be emitted, and thereby penetrate into the surrounding geologic formation, for inducing an oscillating signal in any electrically conductive media within the formation that may be detected and measured by the Receiver before the Metallic Transparency is closed by the Transparency Flux falling below the level **420** required to achieve saturation.

In Figure 2, the high frequency Transmitter Signal **411** is illustrated being pulsed at less than 0.5 millisecond rates. If the lower frequency Transparency Current **401**, generated by the Saturation Coil **551**, is pulsed or activated "on" for 10 milliseconds **430**, there is sufficient time for twenty Transmitter Signals (e.g., with a wavelength of only 0.5 millisecond) to be emitted through the saturated Casing and into the surrounding geologic formation. As explained in the preceding paragraph, these 20 oscillating signals **411** emitted during the "on" pulse of the Transparency Current **401** may induce oscillating eddy currents that may be detected and measured by the Receiver located within the Casing and comprising part of the Logging Tool subject of this invention.

For most applications, a power source of **300** watts or less is sufficient to create the Transmitter Signal and Transparency Current. For thicker material, strong pulses and signals may be generated by utilizing the charge storing capacitors **561**. The capacitors **561** are slowly charged then quickly discharged through a switch contact and then through the low impedance large coil **551**. At the same time, the higher frequency small signal coil **300** is pulsed.

With reference to the preceding abbreviated outline of the invention and Figure 1, the invention comprises the following steps and utilizes the referenced components and sub-components: (1) the Saturation Coil **551**, when energized, acts as an electromagnet. The Saturation Coil creates one or more fields of magnetic flux adjacent or near the Well Casing (not shown). The Saturation Coil creates a partial or full magnetic saturation within at least a portion of the Well Casing immediately proximate to the Saturation Coil **551**. Saturation results in the magnetic permeability of the Well Casing being substantially lowered. When fully saturated, that portion of the Well Casing cannot absorb further magnetic flux, thereby allowing additional flux to pass through that portion of the well casing. In such a state, that portion of the Well Casing has become Metallically Transparent to magnetic flux. In order to create a full Metallic Transparency, the full saturation must extend through the thickness of the Casing. (2) The Transmitter **300** then creates one or more fields of additional magnetic flux having frequencies preferably equal to or greater than the saturation flux. The second field of magnetic flux is engaged with the section of full or partial saturation (having greatly reduced magnetic permeability) allowing the Transmitter flux to pass through the Transparency of the Well Casing and enter the surrounding geologic formation. (3) Media in the surrounding formation that contains electrically conductive properties interact with the oscillating magnetic flux created by the Transmitter **300**.

Through basic electromotive forces, a separate oscillating magnetic flux is induced in the electrically conductive media. (4) The induced magnetic flux travels back to the Well Casing. As in step No. 1 above, the same or similar Saturation Coils **551** create a Transparency near the Receiver **580** so that the induced magnetic flux can be detected and measured through the Casing. (5) The Receiver converts the induced flux into electronic signals that are filtered and processed in order to determine the resistivity of media located outside the Casing. The received signal is processed using various electronic components (which may be located within the Electronic Component **570**) to concentrate and magnify the reacted oscillating magnetic signal. The invention may contain means **582** to electronically null the Transmitter Flux to minimize direct transmission of flux from the Transmitter **300** to the Receiver **580** and to minimize the interference of electronic noise. The transmitted signal is compared to the received signal and, using the changes in amplitude and phase, the resistivity is determined and displayed. These signals are then sent to the Output Display **583** for further processing, display, and recording.

Figure 3 illustrates the Logging Tool **500** containing components of the invention installed within a housing **572** configured to fit within and be lowered into a Well Casing **110**. The outside diameter of the logging apparatus of the present invention ("Logging Tool") allows the Logging Tool **500** to be lowered and raised along the axial path of the Well Casing **110**. It should be noted that a Logging Tool may be configured also for utilization within the production tubing installed inside a Well Casing. The standard communication **588** and power cables **568** that are used currently for production systems provide the linkage from the Logging Tool components located within the Housing to the surface controls. The Logging Tool needs no more power or special communications than is already available by means of existing logging tool systems.

In other embodiments, the power for operation of the Logging Tool may be provided by batteries (not shown) within the Housing **572**. In yet other embodiments, the Logging Tool can be configured with a plurality of components. For example, multiple Receivers could be utilized with one or more Transmitters. In still other embodiments, the Logging Tool components may be configured in series or parallel. Other embodiments may utilize a plurality of components to achieve transparencies, magnetic flux transmission and reception in multiple directions within the same vertical depth. The Tool may also be configured with a plurality of Housing components interconnected and containing multiple configurations of components, i.e., Transmitters, Receivers or Electronic components. This may facilitate measurements being made in multiple directions or to make multiple measurements for increased accuracy, including measurements with multiple frequency or different Lensing or Transparency configurations. Figure 8 illustrates an example of this configuration of multiple Transmitters, etc.

In the preferred embodiment of the invention, the Housing **572** consists of a non-permeable material such as stainless steel. It may also be manufactured of material that is also not electrically conductive, such as a ceramic or glass fiber reinforced material, e.g., a fiberglass structure. Again, it should be noted that Figures 3 and 8 illustrates a bistatic configuration of the invention.

Figure 3 shows a separation distance "D" 910 between the Transmitter **300** and Receiver **580**. Figure 3A illustrates another embodiment of this configuration, but with multiple Receivers **580A**, **580B** and **580C** built into an array for improving signal resolution or detection of signals from electrically conductive media within the formation and at varying distances from the Casing. The Transmitter **300** and Receiver **580A**, **580B** and **580C** may each be incorporated into or used in proximity

to separate Saturation Inducers (not shown). A single Transmitter Signal can be used to detect electrically conductive media at varying distances by locating separate Receivers at varying distances from the Transmitter.

Within the near field, the distance of preferred signal reception will be a function of the distance "D" of the Receiver from the Transmitter, e.g., **910** or **914** or **915**. Lines **181**,**182** and **183** represent 3 flux lines of the same Transmitter Signal. The Receiver **580A**, located distance **910** from the Transmitter, will receive signals from electrically conductive media located along the arc of flux line **181**. The most distant signal will be detected from an object at a distance **911** from the Casing. Receiver **580C**, located distance **915** from the Transmitter **300**, will receive signals from electrically conductive media located along line **183**. The most distant signal will be at a distance **913** from the Well Casing. The geometry of the configuration results in the most distant signal for any Transmitter/Receiver combination will be at a point between the Transmitter and Receiver. The greatest distance capacity will not exist directly in front of the Transmitter. It will be appreciated that the power required to generate a signal detectable by **580C** will be significantly greater than the power to create a signal detectable by **580A**.

Figure 4A is a single axis Magnetic Transparency Generator (Saturation Inducer) device **501** that may be utilized for the Logging Tool subject of this invention. The one-dimensional Magnetic Transparency Generator **501** has magnetic flux lines **140** and **141**, pole orientations North **505** and South **504**. It is of course recognized that the pole orientations may be switched without a change in the subject invention. This Saturation Flux may engage to the Well Casing **110**. It is also noted that most, if not all of the magnetic flux will shift to the side of the Inducer adjacent to the Well Casing. This is attributable to the high magnetic permeability of the Well Casing, i.e., ability to absorb magnetic flux.

Figure 4B is another embodiment of a single axis Saturation Inducer **500** but having two cores **551** and south poles **504**. The two north poles **505** are combined into a Magnetic Culminator **555**. It will be appreciated by persons skilled in the technology that the Culminator must be of sufficient magnetic permeability and mass in order that it not be saturated by the Saturation Flux or by a combination of the Saturation Flux and Transmitter Flux.

Figure 4C is a two-axial Magnetic Transparency Generator device **500** utilizing a Magnetic Culminator **555**. The two-axial cross-flux Magnetic Transparency Generator is adjacent to the Well Casing **110**. The four like poles **504** are connected to four separate cores **551**. The opposing magnetic poles are contained within the mass of the Magnetic Culminator **555**. Figure 4D is a three axis Magnetic Transparency Generator device **500** also incorporating a Magnetic Culminator. The three axis device is adjacent to the Well Casing **110**.

Figure 5A and Figure 5B illustrate Magnetic Transparency Generators comprises of elongated coils wrapped upon highly permeable cores. As with the Magnetic Culminators, the Saturation Cores must not become saturated by the Transparency Flux. The illustrated configuration of the Saturation Circuit is advantageous for use in the present invention since it allows a strong Saturation Flux to be generated in the relatively narrow space of a Well Casing. In regard to Figure 5A, the complete length of the Saturation Coils **551** contribute to the magnetic flux generated between the Magnetic Culminator **555** and each South pole **504**. Similarly, for the configuration illustrated in Figure 5B, the complete length of the Saturation Coil **551** contributes to the quantity of magnetic flux (flux density) existing between the South pole **504** and North pole **505**. This is important since the length of the coils can greatly exceed the space **970** between the magnetic poles. It has been found that electromagnetic coils

wrapped on a core for at least a distance of up to 100 diameters of the core diameter still contribute to the pole strength and the amount of magnetic flux existing between the two magnetic poles.

Figures 5C and 5D illustrate Saturation Inducers **501** incorporating both the Transmitter **300** and Receiver. This configuration is termed a monstatic configuration. The illustrated Saturation Inducer is configured to create a single Transparency in the Casing **110**. The Saturation Coil **551**, Transmitter **300** and Receiver **580** are each nulled 90° to the other. Figure 5C illustrates the Saturation Flux lines F1 through F4 engaged with the Casing. The ends **506** of each pole **504** and **505** are curved to conform to the interior curvature of the Casing **110**. The gap **950** between the Logging Tool **500** prevents an electric current between the Logging Tool and the Casing. Figure 5D provides another illustration of the Logging Tool. The surrounding geologic formation is also illustrated **150**.

Figure 5E illustrates a Magnetic Culminator **555** that incorporates a Transmitter **300** and a Receiver **580**. One face **506** of the Magnetic Culminator is designed to conform to the concave interior surface of the Casing. In the preferred embodiment, the axis of the Transmitter Coil **300** is orthogonal to the axis of the Receiver Coil **580** and that both are orthogonal to the axis of the Saturation Coil **551A** and **551B**.

Figure 6A, 6B and 6C show the geometry of the Saturation Flux **140** engaging the Casing **110**. Figure 6C illustrates a configuration with the Transmitter **300**, wound around the Magnetic Culminator **555**, is more centrally located in relation to the magnetic flux lines engaging or penetrating the greatest distance into the depth **975** of the Casing **110**. In Figure 6B, two opposing South poles are brought together or in close proximity between two North poles. The magnetic flux field lines emitted from the opposing South poles push the flux field out into the Well Casing **110**. However a large unsaturated volume region remains.

Figure 6C shows the use of the Magnetic Culminator **555** containing two like poles **505**. It has already been demonstrated that multiple like poles may be combined into a single Magnetic Culminator. Note that the magnetic flux lines bulge, facilitating the saturation of the thickness **960** of the Casing. This results in the location being well suited for placement of a Transmitter **300**. Note that the Logging Tool is not in contact with the Well Casing as shown by the gap **950**.

It has also been found that enhanced Magnetic Coupling, i.e., penetration of the Well Casing **110** by the Transparency Current without saturation, is achieved utilizing this Saturation Inducer configuration **500**. In this case, coupling allows more energy to be transferred to the Casing **110** from the Saturation Inducer **500**.

Moreover, it is the goal of the invention to concentrate the magnetic flux energy of the Transparency Current into a minimal volume region. For the configuration illustrated in Figure 6A, the spacing between the two unlike poles **970**, however, is limited by the thickness of the casing **960**. Therefore, if the material is "T" inches thick **960**, to saturate all the way through the Casing the spacing **970** between the two poles **504** and **505** must be at least "T" inches apart in the simple configuration shown in Figure 6A. However by "bucking" the poles, the same "T" inches depth of penetration may be achieved but with less than "T" inches separation between like poles. The benefit of minimizing the distances between the poles is that less energy, i.e., amp turns, are required for partial or full saturation of the subtended Casing. If very long distances are to be measured outside and away from the Casing, then it is advantageous if the Transmitter and Receiver are positioned in a bistatic array, i.e., each located within or in conjunction with separate Magnetic Transparency Generators. This facilitates nulling and reduces the energy requirements.

As the number, diameter and length of the coils increases, the mass

and the permeability of the Magnetic Culminator must also increase in order to achieve the concentration of magnetic flux energy of the Transparency Current. It will also be appreciated that neither the Magnetic Culminator nor any other component of the Magnetic Flux Generator is in electrical contact with the Casing.

It will be appreciated that utilization of the bistatic configuration, illustrated in Figure 3 and Figure 3A to measure the thickness of the Casing **110**, will consist of the measured average of the casing thickness over the distance **910** (or **914** or **915** as applicable). However, it is possible to obtain measurement by nesting the nulled Receiver inside the Transmitter Coil **300**. This configuration is shown in Figure 7. In Figure 7, the area of wall thickness measurement is a function of the Transmitter Coil diameter. For the above reasons, Figure 7 illustrates a preferred embodiment of the invention, allowing compact size, decreased mass and energy consumption, and enhanced accuracy.

Figure 8 illustrates another bistatic configuration with multiple, simultaneous direction measurement capability.

Figure 9 illustrates an embodiment of the invention wherein the Saturation Coil **551** and the Transmitter Coil **300** are separately wrapped around the same Flux Circuit Core **552**. The Flux Circuit Core is a simple cylindrical shape with both the Saturation Coil **551** and the Transmitter Coil wrapped in parallel around the axis of the Flux Circuit Core **515**. Since the Transparency Coil **551** and Transmitter Coil **300** have the same diameter, they will have the same magnetic moment (amp turns/meter)

For the reasons stated previously, it will be appreciated that the Transparency Current can not be allowed to saturate the Flux Circuit Core **552**. Further, the Transmitter Current will generate eddy currents in the Flux Circuit Core. Further it will be appreciated by persons skilled in the art that the greatest saturation will occur along the circumference of the

Flux Circuit Core in as much as the permeability of the near saturated or partially saturated Flux Circuit Core will be lowest at the circumference, i.e., edge of the cylinder. Since the permeability of the Barrier Material will approach the permeability of air, the angle of refraction of the magnetic flux (not shown) induced by the eddy current within the Flux Circuit Core will increase from the perpendicular. It will be further appreciated that this configuration has created or utilized Magnetic Lensing capacity within the Magnetic Transparency Generator. This configuration also is a preferred embodiment due to its compact size, energy efficiency, accuracy of measurement and ability to utilize Magnetic Lensing. Figure 22 also illustrates the placement of a Receiver Coil **580** nulled to the Transmitter Coil **300**.

Figure 10 illustrates another embodiment of Logging Tool **500** used in conjunction with a single Magnetic Transparency Generator to create the necessary Metallic Transparency to practice the present invention. The Logging Tool **500** comprises an outer cylindrical portion **202** and an inner cylindrical portion **204**. The Transmitter, Receiver and Saturation Coils are disposed on, in or around the outer cylindrical portion **552B** and the inner cylindrical portion **552A**.

Figure 10A illustrates an embodiment of a Logging Tool **500** used to generate a Transparency with respect to a material **110** for practicing the present invention as could be adapted in Figure 10. A Transmitter Coil **300** is disposed at the remote end of the outside diameter of the inner cylindrical portion **552B** of the Saturation Core. A Saturation Coil **551** is disposed at the inner end of the outside diameter of the inner cylindrical portion **552A** of the Saturation Core. A Receiver Coil **580** is disposed within the inside diameter of the inner cylindrical portion **552A** of the Core. The Receiver Coil **580** can be located at different positions using a shaft **232** which telescopes within the inside diameter of the inner cylindrical

portion **552A** of the Saturation Core. The telescoping shaft **232** can also rotate using a set-screw adjustment **206** and a set screw housing **208**. Also, wiring **234** can be channeled through the shaft **232**.

Figure 10B illustrates another embodiment of a Logging Tool **500** used for practicing the present invention as could be adapted in Figure 10. A Transmitter Coil **300** is disposed at the remote end of the outside diameter of the outer cylindrical portion **552B** of the Saturation Core. A Saturation Coil **551** is disposed along the outside diameter of the inner cylindrical portion **552A** of the Saturation Core. A Receiver Coil **580** is disposed within the inside diameter of the inner cylindrical portion **552A** of the Saturation Core. The Receiver Coil **580** can be located at different positions using a shaft **232** which telescopes within the inside diameter of the inner cylindrical portion **204**. The telescoping shaft **232** can also rotate using a set-screw adjustment **206** and a set screw housing **208**. Also, wiring **234** can be channeled through the shaft **232**.

As shown in Figure 11 a Saturation Core **552** is axially wrapped with insulated wire, forming a Saturation Coil **551**, to create a powerful low frequency or D.C. magnetic field along the longitudinal **515** axis of the Core **552**. The Saturation Core is comprised of a ferromagnetic metal or other highly magnetically permeable material used so that the magnetic flux created by the Saturation Coil does not disperse. "Low" frequency is defined by relationship to the frequency of the Transmitter Current wavelengths needed to make a measurement, e.g., if ten wavelengths are needed for the measurement, then the low frequency must be a least 1/10 of the frequency of the Transmitter Current.

Also in Figure 12, one embodiment of the invention shows a separate Transmitter **300** wrapped such that the eddy currents **620** generated in the core have an axis 315 perpendicular to the long axis **515** of the core **552**. This core is then placed in some gap or distance **950** to

the Casing **110** This EM Barrier can be made completely transparent for the Transmitter or, alternatively, an antenna or lens utilizing Partial Transparency. The optimum size of the gap **950** between the core **552** and the Casing **110** is proportional to the magnetic moment of the transmitter/core diameter **990** and any lensing derived from the surface of the core **552** by the Transmitter Current being focused by the Transparency Current.

As previously mentioned, when a gap is present, e.g., insulation causing the space between the Saturation Core **552** and Well Casing **110**, the wrapping of the Transmitter **300** on the Core **552** utilizes this gap to create the Magnetic Lensing effect at the surface of the Saturation Core, analogous to the Lensing that can be created at the Well Casing surface using partial saturation. This Magnetic Lensing counteracts the decreasing Transmitter Flux, i.e., the decrease in the Transmitter Flux density as the distance from the Transmitter or Saturation Core increases. The rate of this decrease in Transmitter Flux density is the inverse cube of the gap distance between the Saturation Core interface to the Well Casing. This is illustrated by the relationship of magnetic flux intensity decreasing to zero as the inverse cubed of the distance (D) **910** away from the surface, i.e., Intensity Plot = $1/D^3$. Note that in this example, the Transmitter is located on the Saturation Core. It will be appreciated by persons skilled in the art that the Saturation Core concentrates the Transmitter Flux. It will be appreciated that in the preferred embodiment of the invention, a ferromagnetic material or other electrically conductive and magnetically permeable material ("EM Barrier") is used for the Magnetic Lensing component.

As illustrated in Figure 11, there is less Lensing in the gap **950** and on the Casing **110** due to the limited penetration of the Transmitter Flux into the unsaturated Core **552**. However, the eddy current generated

within the casing by the low frequency Transmitter Flux will also induce oscillating magnetic flux. The Transmitter 300 induced eddy currents **610** in the Casing **110** are shown in Figure 11. The resulting magnetic flux lines **140**, **141**, **142** and **143** generated from these electrical eddy currents inside the Casing are shown in Figure 11 intersecting the Casing surface perpendicularly **149**.

Figure 12 depicts the change caused by the activation of the Saturating coil **551**. In this embodiment, as shown in Figure 11 and Figure 12, the Transmitter **300** is a separate coil from the saturation coil **551**. It is also assumed that the Transparency Flux current is either D.C. or has frequency much less than the oscillating Transmitter Flux. The magnetic flux field lines **150** of this constant or low frequency magnetic Transparency Current are shown within the Casing **110**. This constant or low frequency magnetic flux lowers the permeability of the Well Casing. The region of greatest influence of the magnetic flux of the Saturation Core **552** is shown nearest the surface of the Well Casing **110** and decreasing into the Casing. As the permeability of the Casing is reduced by the increasing magnetic saturation from the Transparency Flux, the Transmitter flux lines begin to change their surface angle of impingement away from the perpendicular. It can be readily appreciated that the impingement angle **148** at the surface will be the limited to the flux angle that would exist if the Casing was not present. This limit is approached as the permeability of the Casing approaches unity with the permeability of the matter or media in the gap or space, e.g., air, adjacent to the Casing. This changed impingement angle is shown in Figure 12 near the region of the Core's greatest influence in having reduced the permeability on the Casing. Further away radially from the Saturation Core, the magnetic flux lines again impinge perpendicularly to the Well Casing surface **149**.

Also shown in Figure 12 is a plot **180** of the resulting flux intensity

variation along the centerline **910**. This shows an intensity spike **185** due to the concentration of the field at some fixed distance away from the Casing surface. This flux field concentration is the same effect as would be obtained from an optical "lens" and is termed "Magnetic Lens" effect. The distance away from the EM Barrier plate at which these flux lines are concentrated is called the "Magnetic Focal Length." The place these flux lines are focused is called the "Magnetic Focal Point" **186**. This Focal Point may be moved toward or away from the Barrier Material **100** by reducing or increasing the magnetic moment of the Transmitter and the Transparency Coil or the geometry of the magnetic fields in the metal plate.

It will be appreciated that there is another embodiment wherein the Transmitter Signal coil is superimposed electronically on the coupling Transparency coil. There are separate advantages to this configuration and the configurations shown in Figures 11, 12, etc. When limited by physical and power constraints, it is advantageous to utilize the configuration wherein the saturation coils and transmitter coils are physically separated but magnetically coupled. Both configurations are claimed as part of this invention.

In Figure 13A, the Transmitter Coil **300** is rotated to be approximately parallel to the Casing **110**, ignoring temporarily that the Well Casing surface is necessarily curved in forming the cylindrical shape. The Transmitter induced eddy currents **620** generate the magnetic flux field having a geometry illustrated by field lines **140-143**. Note the density of the magnetic flux field lines along line **910** as the flux field emerges from the partially saturated Casing surface **110**. Supplemented on the Figure 13A is the plot **181** of the decrease in magnetic field intensity **180** as the distance from the surface **910** increases. The magnetic flux field intensity **180** decreases to zero along the plotted line **181**. This illustrates that the

intensity decreases in relation to the distance (D) **910** away from the surface, i.e., Intensity Plot = $1/D^3$.

Figure 13B shows the Transmitter induced magnetic flux field **140**, **141**, **142** and **143** when the Saturation Inducer **500** is turned on. There is a concentration of the flux lines off the centerline **910** and Magnetic Lensing occurs in a different geometry from Figure 12. The shape of the Transmitter induced magnetic flux field has changed. The focused flux fields create a "Focal Circle" **187** or "Focal Plane" instead of the focal point **186** geometry illustrated in Figure 12.

There are advantages to winding the Transmitter coils **300** in this manner with respect to the surface of the Well Casing **110**. The main advantage is that all elements of the Transmitter coils can be made equidistant from the surface of the Casing **110**, therefore inducing an eddy current uniformly parallel or perpendicular to the surface of the Well Casing and inducing a symmetrical magnetic flux field. If non-uniform eddy currents were desired, then it would be possible to rotate the axis of the Transmitter coil **300** to be some angle between perpendicular (as in Figures 11 and 12) or parallel (as in Figures 13A and 13B) to the metal plate. (This geometry is illustrated in Figure 19.)

It will be appreciated that there is an eddy current generated in the core **552** and opposing the Transmitter Current. As the Transmitter coil 300 is moved axially along the core **552** and away from the end of the cylindrical core, more of the energy of the Transmitter is consumed by this opposing eddy current. Note that this decrease of Transmitter energy is experienced in spite of the gap **950** between the core **552** and the Casing **110** remaining relatively constant.

Using this Magnetic Lensing technique allows the Transmitter power to be minimized yet allows resistivity measurements at distances within the Geologic Formation not possible without the consumption of much greater

power and increased size of the Magnetic Transparency Generator subject of this invention.

Figure 14A and Figure 14B illustrate another embodiment of the invention with the curved Well Casing surface **110**. It will be appreciated that, for configurations of the Logging Tool optimizing a compact structure, achieving increase energy efficiency and using nested Receivers and Transmitters, the effect of the curved surface of the Casing will be minimized and the Lensing effect illustrated in Figures 12 and 13B will be increasing applicable. It will also be appreciated that known techniques for creating flexible ferromagnetic shapes of parabolic or similar geometry may be used to allow adjustment of the magnetic focal distance.

Figure 15 shows beam directivity and steering capabilities by an inter-play of a plurality of Saturation Inducers, e.g., **500A**, **500B** and **500C** and one Transmitter **300**. In this Figure, the Saturation Inducer **500A** and **500B** are creating the maximum permeability reduction within the Well Casing **110** proximate to Transmitter **300** and Saturation Inducer **500A** This creates the maximum bending of the flux lines **140 – 143** induced by Transmitter **300** towards Saturation Inducer **500A** . There is a maximum beam steering available by this single Transmitter technique.

Figure 16 shows two Transmitters, **300A** and **300B** with bucked Transparency magnets **551A** and **551B**. The Transmitters are both wound with their coils substantially parallel to the Casing **110**. To deflect the Transmitting Current **150** and **151** from **300A** to the top, Transmitter **300B** should be increased in strength (at the same frequency) and Transparency Current of **500B** must be increased over Transparency Current.of **500A**.

In Figure 17, another Transparency magnet **500C** is added to increase the current to the distance D $_{2,3}$. **910**. This will bend the flux field **140 - 143** downward while Transmitter **300A** is made much more powerful than Transmitter **300B** to push the flux field down.

In Figure 18, another embodiment of the invention relating to beam movement is shown. This embodiment utilizes the Transmitters **300A** and **300B** having equal diameters but oriented at 90° to the other. Again, it is possible to use combinations of Transmitters and Magnetic Transparency Generator's **500A** and **500B** having unequal saturation strengths to bend the flux field.

Figure 19 shows the Transmitter **300** at an oblique angle to the Well Casing **110**. It is also oblique to the Transparency Coil **551** and Transparency Core **552**. The Well Casing is not fully saturated and the oscillating magnetic flux field of the Transmitter **300** induces eddy currents **610**. These eddy currents are also at an oblique angle to the surface of the Casing **110**. Further, the eddy currents **610** induce a corresponding Magnetic Flux Field radiating out of the Well Casing **110**. It should be noted that the field lines do not extend out of the Casing toward the Saturation Inducer but rather field lines stay in close proximity of the Casing surface.

In regard to the Conductivity/Resistivity Measuring System of the present invention, it is possible to greatly improve existing methods of measuring electrical conductivity of the geologic formation by using a spectrum of frequencies rather than one frequency. In addition, the metallic permeability must be measured to accurately depict the effects of the Well Casing upon the measurement of conductivity. Using a range of frequencies allows a single device to function where the Casing thickness may vary from zero (no metal) to multiple inches thick. Using the same frequency over such a wide range causes a large loss of resolution and accuracy. Therefore, for a given range of material thickness, a particular group of frequencies will provide improved resolution and better accuracy.

To eliminate the effects of a varying metallic permeability, it is necessary to create a local Metallic Transparency with the permeability as

close to unity as possible while the Transmitter frequency is being varied. Then, while the Transmitter frequency is held constant, changing the amount (amplitude) of the Saturation Current will vary the permeability of the Casing or other Barrier Material.

One embodiment of the present invention as broadly described herein is a method for creating a spectral EM frequency metallic thickness measurement using Metallic Transparencies. In order to calculate the thickness of a Casing or other Barrier Material with unknown permeability and conductivity, empirical testing is used to first approximate the conductivity and permeability. Conductivity and permeability can be approximated in any order using techniques herein discussed.

As the frequency increases, the conductive losses increase until the skin depth becomes much less than the thickness of the Barrier Material. As used herein, "skin depth" is proportional to the inverse of the square root of the product of permeability, conductivity and frequency.

Figure 20 illustrates the relationship between signal frequency and penetration depth for a cross-section of a piece of metal with a conductivity, a permeability and several imposed frequencies f_x, for the present invention. For a wave of constant amplitude and varying frequency, and a metal with the same permeability and conductivity, it is known by skin depth theory that a lower frequency penetrates deeper than a higher frequency. Therefore, one can find an optimum frequency range that can characterize the metal conductivity. For constant length L and varying frequencies, the penetration depth δ is:

$$\delta = \left(\frac{1}{e}\right) L$$

and

$$\delta = \frac{1}{\sqrt{\sigma \mu_r \mu_o f}}$$

where

δ = penetration depth,

f = frequency,

σ = conductivity

μ_r = relative permeability, and

μ_o = absolute permeability.

In Figure 20, the relationship of frequencies is

$f_6 > f_5 > f_4 > f_3 > f_2 > f_1$.

The first step to calculate the thickness of the Casing is to generate a magnetic flux adjacent to or near the Casing to be measured. The magnetic flux must be of sufficient magnitude to saturate the Casing. The Saturation Current may be generated by a permanent magnet, an electromagnet powered by DC current or AC current. The AC powered EM waves will preferably be of a relatively low frequency. Upon achieving saturation of a portion of the Casing, a second magnetic flux is generated with specific constant amplitude and engaged with the saturated Casing. The resulting magnetic signal from the Casing is monitored using a Receiver. The Receiver is located adjacent to or near the Casing to be measured. The Receiver may be either co-located with the Transmitter or at a distance away, e.g., as in a bistatic configuration. The Transmitter frequency is increased incrementally while the amplitude is held constant and the received signal is monitored.

As required by skin depth theory, for a given wave of constant amplitude and varying frequency, the lower frequencies penetrate deeper

into a piece of Casing than the higher frequencies. The higher the frequency, the greater loss of signal, i.e., increased attenuation. See Figure 20. Therefore, an oscillating magnetic flux of a specified frequency can be generated and engaged with the Well Casing. The received signal is monitored. The frequency of the Transmitted Flux is increased in a stepped fashion while continuing to monitor the received signal. The amplitude of the Transmitted Signal remains constant. As the frequency of the Transmitted Signal is incrementally increased, for example by stepping, the received signal will attenuate. With the amplitude held constant, the maximum frequency of the Transmitter Signal capable of penetrating the Casing is therefor determined when the Receiver is no longer able to detect a signal. The last frequency to generate a received signal is the "maximum penetration frequency." The Maximum Penetration Frequency is used in the present invention to determine material thickness.

The second step in calculating the thickness of a material with unknown permeability and conductivity is the approximation of permeability. Using the same Transmitter, Receiver, and saturation procedures described in the first step, a Saturation Flux is generated near or close to the Well Casing to be measured. The Saturation Flux has a known yet variable current. A Transmitter Flux of known and constant frequency and amplitude is generated at or near the Well Casing within a zone to be effected by the Saturation Flux. A Receiver monitors the Receiver Signal from the transmitted signal returning for generating a resulting electromagnetic response. While monitoring the received response and holding the Transmitter Flux frequency and amplitude constant, the Saturation Current is increased incrementally. Thus, the Receiver Signal will generally mirror the steps of the Saturation Flux but at different amplitudes than the Transmitter Flux. (See Figures 21B and 21C.) As the Saturation Flux increases, the Well Casing becomes more

and more transparent to the Transmitter Flux (maintained at constant amplitude and frequency), thus, causing the amplitude of the Receiver Signal to increase proportional to the stepped increases in the Saturation Flux. The stepped incremental saturation is continued. while the Transmitter Flux is held at the constant amplitude and frequency and the resulting increments in the Receiver Signal are monitored. This is continued until no further changes are registered by the Receiver in response to increases in the Saturation Flux. The point at which the received signal registers no change may be called "total saturation." See Figure 21C. Once Total Saturation is achieved, increases in the current or amplitude of the Saturation Flux have no effect upon the Received Signal. Thus, the Transmitter Flux is coupled with the Casing. As the Casing becomes more saturated, (and its permeability approaches 1) the Casing becomes increasingly transparent, resulting in more of the Transmitter Flux penetrating though the Casing. The current history and the associated received signal, as illustrated in Figure 21A, 21B and 21C, provide for full or partial saturation of a localized area. Further, the current history and the received signal information can be used to mathematically determine the permeability and thickness. Once approximation is obtained on either permeability or conductivity, the other variable can be determined and the material thickness can then be calculated.

The technique of the present invention for calculating the thickness of a material with unknown permeability and conductivity can be used to further classify various materials (and the thickness of such materials) such that a general lookup table can be created. The general lookup table can contain known results from numerous test samples allowing for quick lookup and display of thickness based on known samples meeting the test criteria. The test criteria can be for a range of thickness for specified materials having the same permeability and conductivity.

It order to obtain an accurate measurement of permeability and/or conductivity, electronic and geometric nulling are required. Geometric nulling positions the Transmitter, Receiver and Saturation Coils in the optimum locations for the particular system designed. Various designs are provided yielding excellent results. Also, an electronic nulling circuit can simultaneously null all of the frequencies at once. Pursuant to practicing the present invention as described herein, one skilled in the art will know and appreciate how to arrange the Transmitter, Receiver and Saturation Coils in optimum locations for the particular system being used, and will know and appreciate how to simultaneously null all of the frequencies at once to provide electronic nulling.

Figure 5D illustrates one embodiment of a Magnetic Transparency Generator **501** used to generate the Transparency Current required to practice the present invention. The Transparency Current Generator **501** is utilized to completely saturate the intended Well Casing **110** volume region **600**.

In Figure 22, the bistatic Logging Tool **500** consists of two separate Magnetic Transparency Generators **593** and **595** contained within a housing **109**. The Magnetic Transparency Generator **593** incorporates a Receiver with a Receiver Coil **581** wound orthogonal to the Saturation Coil **551**. The Magnetic Transparency Generator **595** incorporates a Transmitter **300** with the Transmitter Coil **301** wound parallel to the Saturation Coil. The distance between the Receiver Coil **581** and the Transmitter Coil **301** is the distance "D" **910**. The Logging Tool **500** is in operative association with a Well Casing **110** having a defect **599A**. It can be appreciated by those skilled in the art that in the bistatic configuration illustrated in Figure 22, the distance D must be sufficiently small relative to the geometric size of the defect **599A** in order that the Logging Tool may detect the defect. Accordingly, the accuracy of the casing thickness

calculation is limited by the mass to be evaluated and the displacement distance "D" **910**.

The limitation of the displacement distance can be essentially eliminated by a utilization of a single Magnetic Transparency Generator as illustrated in Figures 5E and 7 in operative association with a Magnetic Culminator **555**. The Transmitter **300** and the Receiver **580** are both on the same Culminator **555**. The displacement distance D between the Transmitter **300** and the Receiver **580** is essentially zero because of the close configuration of the Transmitter and Receiver. In the illustrated configurations the Receiver and Transmitter are geometrically nulled. The configuration illustrated by Figure 7 has the additional advantage of adaptation to the adjustable nested configuration of Figure 10B wherein the Saturation Core is replaced with a Magnetic Culminator. The intensity of the frequencies received will show the metal thickness. For example, if all the higher frequencies are attenuated, the metal is thick. If all the high frequencies are detected with little attenuation of the low frequencies, the metal is thin. For a given power, the displacement distance D between the transmitter **300** and the receiver **580** determines the resolution of the thickness measurement. The resolution effects the size of the defect measurable.

Also, Figures 5A through 5E illustrate alternate embodiments of the Metallic Transparency Generator **501** for use with the present invention. The Metallic Transparency Generator illustrated in Figure 5A comprises flux circuit core **552** upon which the Saturation Coil **551** is wound, two like magnetic poles **504** between which is a Magnetic Culminator **555**. The core **552**, upon which the Saturation Coils **551** of the electromagnet are wrapped, is located between each pole **504** and the Culminator **555**. Preferably, the Magnetic Transparency Generator is contained within a housing (not shown) and connected to the power source and

instrumentation by conventional means, (also not shown). It will be noted and appreciated by persons skilled in the technology that the Magnetic Transparency Generator **501** is not in contact with the Well Casing **110**..

The complete Magnetic Transparency Generator **501** incorporates the Flux Circuit Core **501** for providing a Metallic Transparency that is illustrated having a width W **920**, a height H **930** and a thickness L **960**. The Transparency may be termed the Target Area. It is appreciated that the Transmitter Coils **300**, the Receiver Coils **580** and the Transparency Coils **551** of the Magnetic Transparency Generator **500** are nulled to each other.

FIG 5C illustrates one embodiment of the Logging Tool **500** of the present invention. The Logging Tool **500** comprises the Saturation Coil **551**, the Transmitter Coil **300**, Receiver Coil **580** and the Well Casing **110**. The Magnetic Transparency Generator **501** is disposed from the Well Casing **110** by a gap G **150**. The Well Casing **110** has a thickness L **160**. The Logging Tool **500** operates by energizing the Saturation Coil **551** for saturating the Well Casing **110**, transmitting a Transmitter Signal from the Transmitter Coil **300**, and receiving a response via the Receiver Coil **580**. The relative penetration is caused by the change in the Saturation Current. Thus, as the Saturation Current increases from i_1, to i_2, to i_3, to i_4 then the penetration depth increases from δ_1, to δ_2, to δ_3, to δ_4, respectively. Figure 5C illustrates the incremental increase in penetration by the field lines F_1, F_2, F_3 and F_4. Also, consideration of the cross-sectional area of each component of the Logging Tool **500** is required to assure that no component goes into total saturation for a specific power requirement necessary to drive the Magnetic Flux across the gap G **950**.

Figure 22 illustrates one embodiment of a bistatic Magnetic Transparency Generator **501** of the present invention. Using the bistatic Magnetic Transparency Generator **501** shown in Figure 22,, the

permeability is driven to unity. Oscillating Transmitter Flux of differing frequencies are transmitted by the Transmitter **300** and related induced magnetic flux signals are monitored with the Receiver **580**. A Metallic Transparency is created by the Saturation Flux of the Magnetic Transparency Generator in a portion of the Well Casing **110**. An oscillating Transmitter Signal is generated using the Transmitter **300** at a preset frequency and constant amplitude. Assuming the first frequency is within the detectable frequency range, the frequency is increased incrementally until the received signal is lost. The last frequency detected prior to losing the received signal determines the Maximum Penetration Frequency detectable in a certain piece of Well Casing **110** of constant thickness, permeability, and conductivity. Using the data and information received in empirical testing for permeability, the material properties and thickness can be very precisely calculated.

Figure 23 illustrates the relationship between the flux field β and the change in H (ΔH) in amp-turns/meter. The permeability μ is plotted. For the relationship between the flux field β and ΔH, the function defining the permeability μ remains the same. Although the function defining the permeability μ remains the same, the value of ΔH for thinner materials moves up the curve faster. Thus, incremental changes in H create a faster advancement up the permeability curve toward saturation. For example, a given H_{L1} corresponds to the value of β_{L1} and a corresponding H_{L2} corresponds to the value of β_{L2}. Thus, the value for L2 moves faster up the permeability μ curve than the value for L1.

Figure 24 illustrates the relationship between the amplitude A_{Rx} of the Receiver Signal and H in amp-turns/meter. As in Figure 23, the slope of the curve in Figure 24 is related to the permeability μ. However, the Receiver amplitude A_{Rx} reaches a different maximum value depending on the thickness of the Casing. For thinner Casing, as with other materials,

the Receiver amplitude A_{Rx} reaches its maximum value at a lower amplitude A_{Rx}. For thicker materials, the Receiver amplitude A_{Rx} reaches its maximum value at a higher amplitude A_{Rx}. Figure 24 illustrates a thinner material having a maximum at A_{R1}, a thicker material having a maximum at A_{R3}, and an intermediate thickness material having a maximum at A_{R2}.

Figure 25 is a graph of amplitude versus time for a bistatic configured magnetic transparency generator of the present invention. The frequency is held constant (fixed) and the Barrier Material, also of constant thickness, and is varied. The bistatic magnetic transparency generator was nulled using copper **902**. Thereafter, the copper was replaced with brass causing the amplitude to vary from the original nulled position **904** to a new position **904**. Since brass and copper have related properties, the dislocation 904 from the copper nulled position **902** is small. However, when the brass is replaced with aluminum the amplitude 906 varies significantly from the original nulled position **902**. Aluminum and copper have significantly different physical characteristics.

METHOD OF PROCEDURE

As the Logging Tool moves through the axial length of the Well Casing, a number of procedures are carried out in the following manner at a particular point.

The value of the Casing permeability is measured by varying the "H" field by increasing the magnetic coils current by fixed amounts.

The Casing conductivity is measured by varying the frequency over some known values.

Using the permeability and conductivity, the Casing thickness may be calculated from the thickness algorithm.

The automatic lensing algorithm will now measure the resistivity with a particular setting for the transmitter power and the magnetic power.

The resistivity reading is adjusted by the permeability and conductivity values.

The corrected resistivity is corrected to a reference resistivity by comparison to a reference inductor.

The tool is now ready to move to the next position.

This sequencing is also shown in Figure 26.

Figure 27 illustrates the apparatus used to demonstrate the invention. Receiver means **580** and Transmitter means **300** were placed in a section of ferromagnetic metal pipe. A Saturation Coil (not shown) generated a Metallic Transparency proximate to the Transmitter and Receiver. This configuration of components within the metal pipe was placed above a tank **196**. The apparatus was activated and measurements were taken of the resistivity of the media below the pipe. Water was added to the tank from an opening at the bottom by means of piping **198**, valve **197** and second tank **195**. This caused the level of the water **190** to rise in the tank **196** below the pipe. As the surface of water approached the pipe, the measured values of resistivity changed. Figure 28 shows the change in measured resistivity **191** compared to the change in water level **190**.

The given description illustrates that the test apparatus has demonstrated the capability to analyze/measure the resistivity in the producing zone just outside the casing for a distance of at least 4 feet. By taking these measurements continuously or over short intervals, the resistivity can be trended. Trending makes it possible for the operator to see very slight changes in resistivity, and will signal even slightly higher concentrations of water in the hydrocarbon reservoir. The invention provides unique information that is important both to the reservoir engineer and to the production engineer, by providing both real-time information and historical trends, useful in managing the production zone and its flows. The present invention also provides information useful in defining the surrounding geology or detecting changes in the geologic formation.

In the foregoing description, a single power level, frequency, and direction is discussed. However, the apparatus can be readily modified by varying the strength and frequency of the transmitted signals, and by adding transmitter/receivers in multiple directions or at different spacing, or by adding complete sets of additional down hole devices at multiple production zones. The apparatus may also be modified in a manner to allow it to contain its own power source. This power source can be a stored electrical power source such as one or more batteries. The apparatus may also incorporate powered devices to propel the apparatus along the axial direction of the Casing. It will be appreciated that this would be of particular benefit when the apparatus is in a substantially horizontal portion of the cased well bore. This capability may also facilitate use of the apparatus in portions of a cased wellbore that contain directional changes. This propulsion capability can be a supplemental means existing means for moving the apparatus through the Well Casing. It may, in other embodiments provide the single means for movement of the apparatus. When combined with data recording and storage capabilities, the

apparatus could operate independent of any attachment to the well head. The means for propelling the apparatus along the Well Casing may include wheel or track devices separately attached to or incorporated into the housing of the apparatus.

The apparatus may also utilize one or more permanent magnets to provide the Saturation Flux. One benefit from the use of permanent magnets is that the electrical power requirements would be less.

Additional embodiments of the apparatus may utilize means to maintain a constant distance between the apparatus and the Well Casing proximate to one or more of the Saturation Inducers. This component may be termed a constant distance control device. This device may employ non conductive or non permeable materials to provide this contact. It will be appreciated that contact between this device and the Well Casing is not for the purpose of transmitting electrical or magnetic energy from the apparatus into the Well Casing. The constant distance control device may also include one or more flexibly tensioned attachments, such as wheels or tracks held by springs. These attachments may also not to be electrically conductive or magnetically permeable. When the apparatus of the this invention includes a cylindrical housing or other shape, the these attachments may be positioned on the circumference or perimeter of the housing (or to an auxiliary device attached to the housing) in a manner that the flexible tension device keeps the constant distance control means in contact with the interior surface of the Well Casing.

In another embodiment of the invention subject of this specification, a single electrically conductive coil may be used to provide the Saturation Flux and the Transmitter Signal. The coil would first be powered with dc current sufficient to create the magnetic flux required for saturation of the Well Casing. The power could then be switched to ac current and multiple wavelengths of oscillating magnetic flux be emitted into the Well Casing.

The power could then be returned to the dc current providing the Saturation Flux. This alternating powering could be repeated in rapid succession, thereby conserving power and space and weight requirements for the device. The Receiver could also be located proximate to the Metallic Transparency created by the dual saturation and transmitter coil. Accordingly, a separate Saturation Coil would not be required to create the Transparency needed detecting magnetic flux transmitted from the exterior of the Casing. This would provide a further reduction of weight, energy and space.

For this embodiment, it will be appreciated that the ac frequency can be controlled and adjusted. It will be appreciated that use of low frequency ac generated magnetic flux will reduce impedance mismatch.

Further modifications and alternative embodiments of this invention will be apparent to those skilled in the art in view of this specification. Accordingly, this specification is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the manner of carrying out the invention. It is to be understood that the forms of the invention herein shown and describe are to be taken as the presently preferred embodiments. Various changes may be made in the shape, size and arrangement of parts. For example, equivalent elements may be substituted for those illustrated and described herein and certain features of the invention may be utilized independently of the use of other features, all as would be apparent to one skilled in the art after having the benefit of this description of the invention.